CZScience: Evaluating the Connection—Stormwater Runoff, Impervious Surfaces, and Pollution

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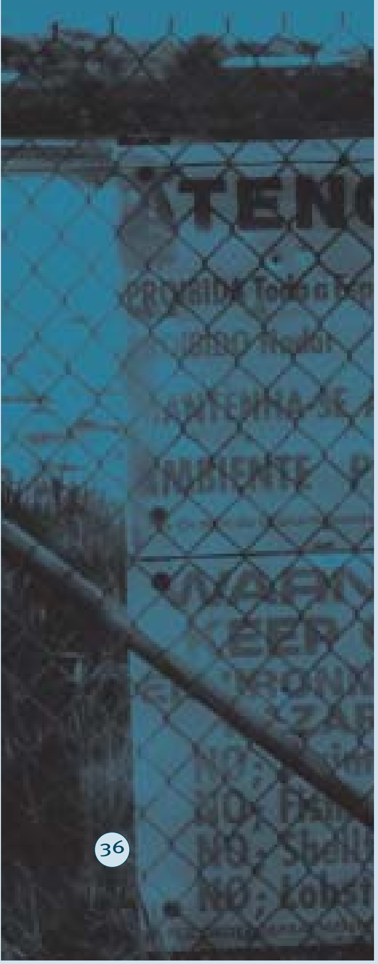
On June 6 and 7, 2002, approximately 2.25 inches of rain fell in the Boston area, much more water than is typically observed during an "average" rainfall in this region of Massachusetts. Most rain events, as observed from 10 years of data collected at Logan Airport, deliver just less than 0.25 inches and typically last for about 6 hours. Over these two days in June, approximately 11.5 billion gallons of water were delivered to the watershed of metropolitan Boston—enough to supply the 1.1 million people living there with household water for approximately 150 days. (In North America, the average person uses about 60-80 gallons of water each day.) However, this stormwater was not captured for our daily use. Where did all this water go and what was its legacy? To better understand the fate and impact of this rainwater, let's start with the concepts of watersheds and the hydrologic cycle.



What Is a Watershed?

Watersheds are defined as geographic areas of land in which all surface and ground water flows downhill to a common point, such as a river, stream, pond, lake, wetland, or estuary. Topography, soil and bedrock geology, and land use (e.g., forested, residential, wetlands, commercial) are important characteristics that affect stormwater drainage within a watershed. For more on watersheds, see www.state.ma.us/envir/mwi/watersheds.htm.

What Is the Hydrologic Cycle?

The hydrologic cycle describes the movement of water (all three forms: solid, liquid, and vapor) through the environment. Generally, this movement is the result of precipitation, runoff, evaporation, and transpiration. Through precipitation, water moves from the atmosphere to the earth's surface in the form of rain, sleet, snow, or hail. Water that ends up on land can return to the atmosphere either by evapotranspiration (water traveling through plants to the leaves where it is released to the atmosphere) or evaporation. When evaporation occurs, water not only moves, but also changes form—liquid water becomes water vapor. Water that flows over the surface may become runoff that directly feeds receiving waters, such as estuaries, lakes, ponds, rivers, streams, and marshes, or it may seep down through the soil as groundwater. Some of the water that enters the soil becomes available for use by plants. Only about two percent of the water taken up by plants is used in photosynthesis (a process where plants convert sunlight to energy or food). Nearly all of the water travels through the plant to the leaves where it is transpired to the atmosphere to begin the cycle again.

Stormwater runoff has a significant impact on the water quality of surface waters, especially in watersheds that contain large amounts of impervious surfaces (i.e., streets and parking lots, roofs, asphalt, brick, stone, and compacted soil). In urban areas, the abundance of impervious surfaces and the lack of plants prevent stormwater infiltration and evapotranspiration, generating large volumes of water runoff and increasing the probability of direct stormwater discharge into local waters thus resulting in what we call nonpoint source water pollution problems.

What Is Nonpoint Source Pollution?

Nonpoint source (NPS) pollution, unlike point source pollution from industrial and sewage treatment plants, comes from many sources. Rain or snow falling through the air starts picking up pollutants even before hitting the ground. Once landing, water that does not penetrate the ground moves over the surface, picking up and carrying away natural and human-made pollutants as it flows over rooftops, streets, parking lots, and other impervious surfaces, finally depositing pollutants elsewhere into the receiving water body. Some of these pollutants may include: excess fertilizers, herbicides, and insecticides from farm lands and lawns; oil, grease, and other chemicals from cars and trucks; sediment from disturbed construction sites, crop and forest lands, and eroding shorelines and stream banks; bacteria and nutrients from livestock and pet wastes; faulty septic systems; and air pollution particles.

Many states report that NPS pollution remains the leading cause of many water quality problems. The effects of NPS pollutants on specific waters vary; however, these pollutants have harmful effects on drinking water supplies, recreation, fisheries, wildlife, and overall aesthetics. Scientists and environmental managers are trying to better understand NPS pollution by quantifying the contributions of stormwater runoff to the degradation of natural waters.

What Is the Latest Scientific Research on Stormwater Runoff in Massachusetts?

Impervious cover has been shown to strongly influence the quality of receiving waters and the health of aquatic habitat (Schuler, 1994, Center for Watershed Protection, 1998). The Center for Watershed Protection (CWP) has demonstrated that significant water quality impacts can result from as little as 10 percent coverage of a watershed by impervious surfaces (CWP, 1998).

The Massachusetts Office of Coastal Zone Management (CZM) has been working to develop new methods of measuring impervious area, which has traditionally been estimated by carefully tracing impervious features from aerial photography using computer-based Geographic Information Systems (GIS). This method can be time consuming and costly when measurements are being made over large areas. CZM has been working with Massachusetts GIS (MassGIS) to simplify this process by refining coefficients that reflect the average impervious surface cover for different types of land uses. For example, CZM has determined that, on average, the surface areas of commercial properties in the Parker River Watershed (northeast Massachusetts) are covered by 64 percent impervious surfaces. The impervious area coefficient for commercial properties would therefore be 0.64. In contrast, landscape features designated as cropland in the same watershed are covered by only nine percent impervious area (i.e., a coefficient of 0.09). By generating these coefficients for each land use category (Table 1), resource managers can easily estimate impervious cover over large areas by pairing them with digital land use maps available from MassGIS. However, large variability can be associated with impervious coefficients (some of the low ones have as much as 100 percent relative standard error!), either within or among different watersheds. The analyst must be aware of these uncertainties and should explicitly state the range of error with estimates relying on impervious cover analyses.

Once the impervious area is estimated, the amount of stormwater runoff can be approximated from studies that establish runoff coefficients based on impervious cover for each of the land use categories. Dreher and Price (1993) observed the relationship between runoff volume and impervious cover as:

$$Rv = 0.05 + (0.009 * \text{percent impervious})$$

Where Rv is the runoff coefficient

Table 1 summarizes the coefficients for impervious cover and runoff for each land use category.

Table 1: Impervious area coefficients and summary statistics generated for each land use category.

Land Use Category	Mean impervious area (ratio)	Rv
Cropland	0.090	0.131
Pasture	0.080	0.122
Forest	0.078	0.120
Wetland	0.055	0.100
Mining	0.067	0.110
Open Land	0.029	0.076
Participation Recreation	0.060	0.104
Spectator Recreation	0.050	0.095
Water Based Recreation	0.343	0.359
Residential I	0.454	0.459
Residential II	0.543	0.539
Residential III	0.305	0.325
Residential IV	0.304	0.324
Salt Wetland	0.016	0.064
Commercial	0.640	0.626
Industrial	0.547	0.542
Urban Open	0.311	0.330
Transportation	0.508	0.507
Waste Disposal	0.218	0.246
Water	0.029	0.076
Woody Perennial	0.154	0.189

Table 1 Note: *Residential I – multifamily, Residential II – smaller than $^1/_2$ acre lots, Residential III $^1/_4$ to $^1/_2$ acre lots, Residential IV – larger than $^1/_2$ acre lots.*

How About an Example?

Let's look at two contrasting sub-watersheds in the larger Boston Harbor Watershed—an urban watershed and a protected Area of Critical Environmental Concern (ACEC)—to illustrate the importance of land cover on how water moves through the watershed and into its ultimate receiving waters. The Weir River ACEC is largely an open-space and low-density residential area occupying approximately 950 acres in the southern portion of Boston Harbor. This ACEC represents diverse wetland habitats that include salt marsh, shallow marsh meadow, shrub marsh, and wooded swamp (Urban Harbors Institute, 2002.). In contrast, the Weymouth Fore River is mainly a dense residential urban sub-watershed located in the southwest portion of Boston Harbor.

The Weir River ACEC is estimated to contain about six percent impervious cover, while the Weymouth Fore River sub-watershed contains about 36 percent impervious cover. Recall that 11.1 billion gallons of water were delivered to the greater Boston Harbor watershed by the 2.25-inch rainstorm that occurred on June 6-7, 2002. Using the coefficients derived above for impervious cover and runoff, stormwater runoff from the Weir River ACEC and the Weymouth Fore River sub-watershed for that same June rain event were estimated as approximately 3.5 (± 1.3) and 152 (± 24) million gallons of stormwater respectively. While the Weymouth Fore River is about 10 times greater in surface area than the Weir, it generated about 40 times more stormwater runoff (that is, about 4 times more stormwater per unit area).

Although this methodology is somewhat subjective, it does provide a sense of the relative contribution of different land uses to the NPS pollution problem. The limitations of the methodology include: a reliance on the analyst's understanding of rainfall characteristics of the region (highly variable) and the assumptions inherent in the coefficients for impervious cover and runoff; the oversimplification of the watershed hydrologic response; and the lack of procedures that measure the uncertainties associated with the model's outcomes and the appropriate field monitoring data for validating model predictions.

Stormwater that runs over lawns, roads, parking lots, and other surfaces ultimately runs to the nearest water body, including the Parker River (left) located within an Area of Critical Environmental Concern.

Conclusions

Given continued water pollution problems, governments at all levels are recognizing NPS pollution prevention and control as vital to water resource protection. Impervious surfaces are viewed as one of the most problematic factors leading to the degradation of watershed receiving waters by stormwater runoff. Measures taken to control stormwater runoff pollution from impervious surfaces may be an important next step to ensuring the protection of groundwater, marshes, streams, rivers, lakes, estuaries, and coastal waters.

In urban watersheds, 30-60 percent of the ground cover may be impervious. The methods for estimating stormwater runoff based on impervious cover of land categories is used to illustrate the importance of land cover types in the retention of rainwater among watersheds. However, model-based estimates are only a starting point for more efficient watershed planning, pollution prevention and control implementation, and habitat protection and restoration.

photo by Bruce Carlisle

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Impervious surfaces, including parking lots, asphalt, and compact soil, are abundant in urban areas.

References

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